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with which is incorporated The Institution of Aeronautical Engineers

Edited for the Council by Capt. J. LAURENCE PRITCHARD, Hon. Fellow

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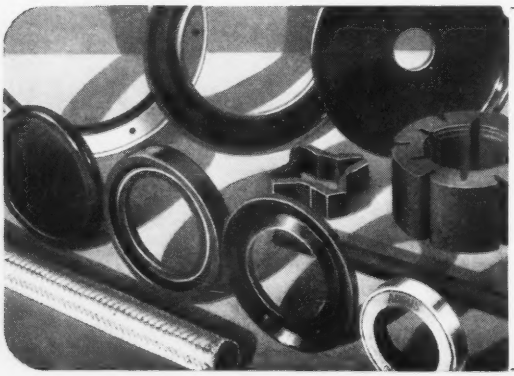

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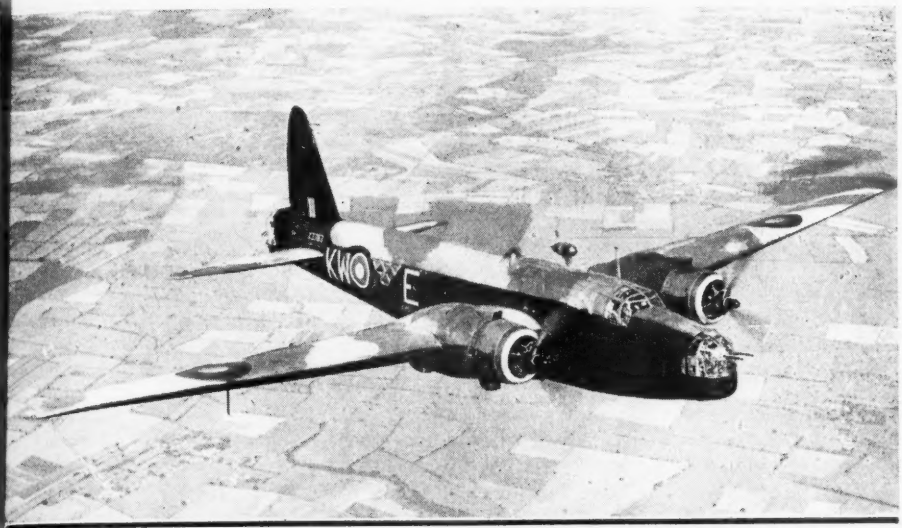

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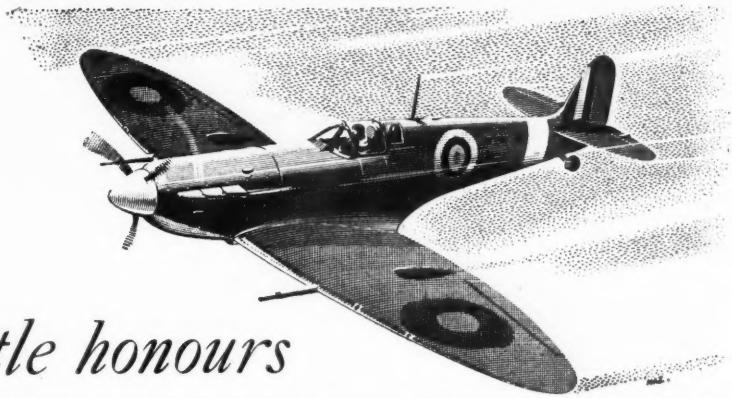

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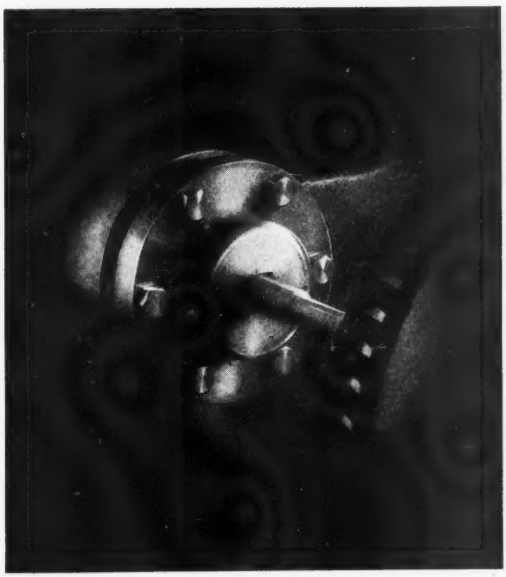

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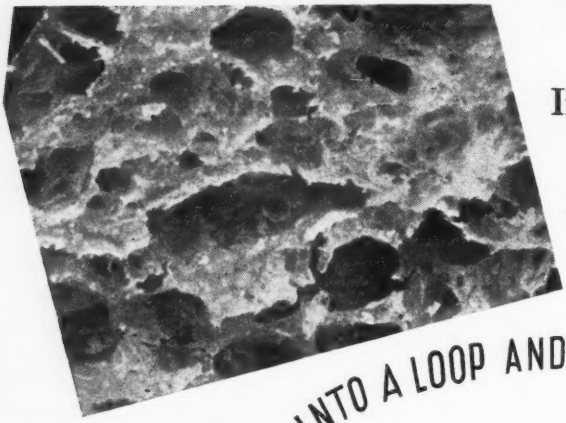

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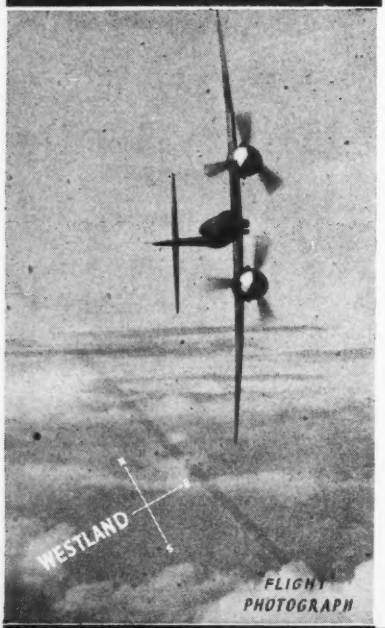

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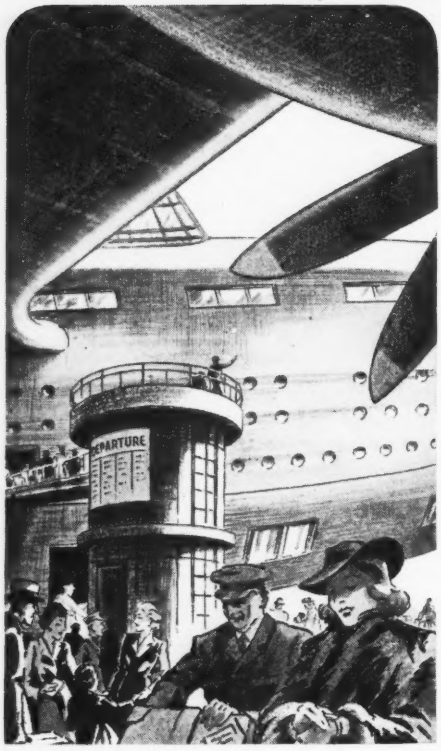

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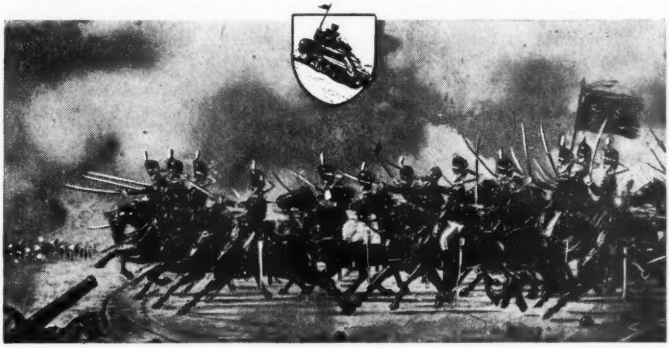

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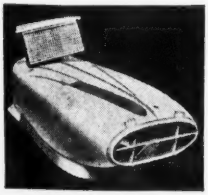

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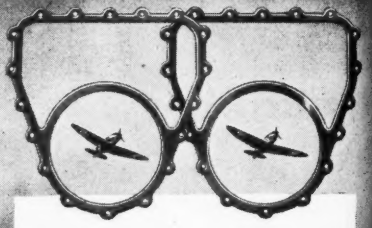

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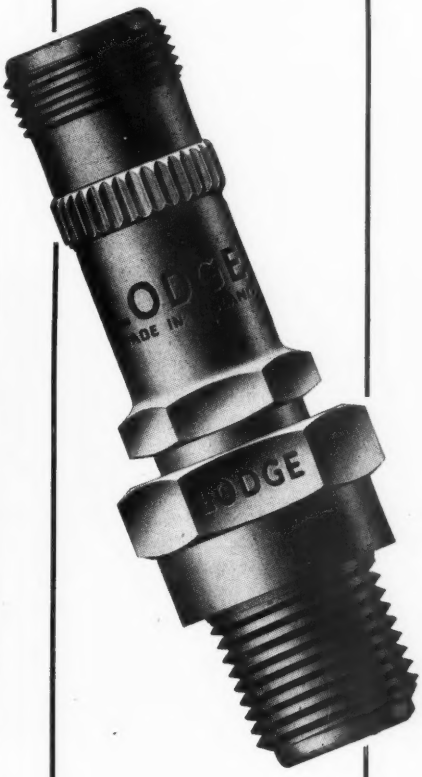

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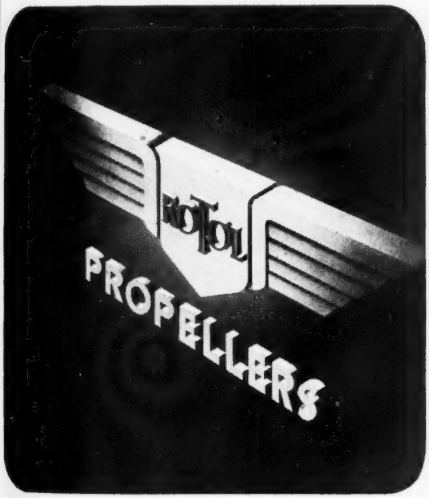

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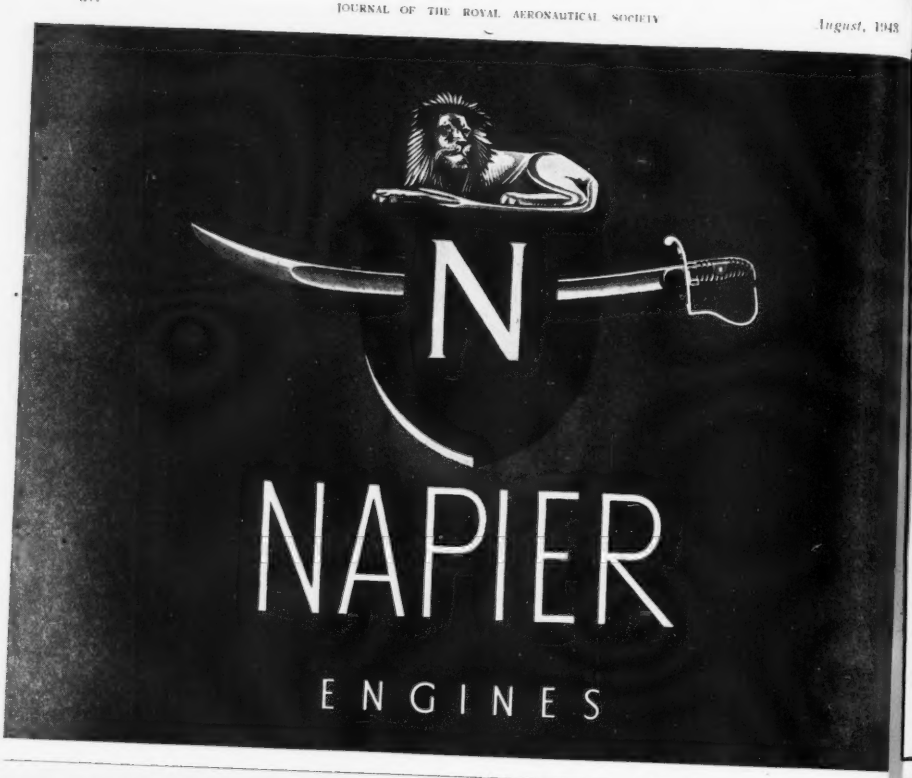
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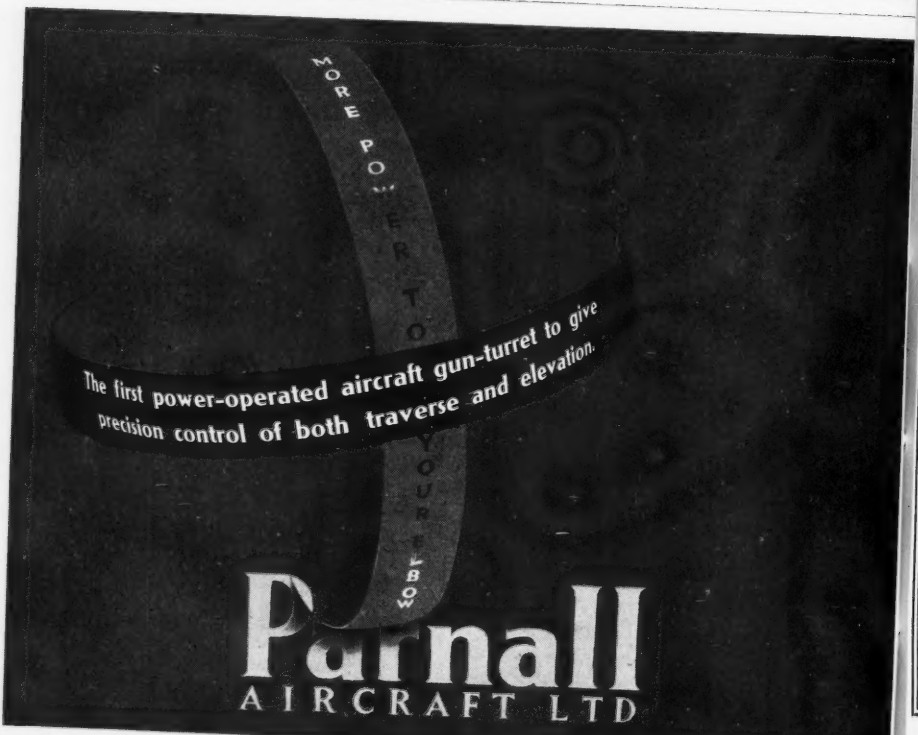
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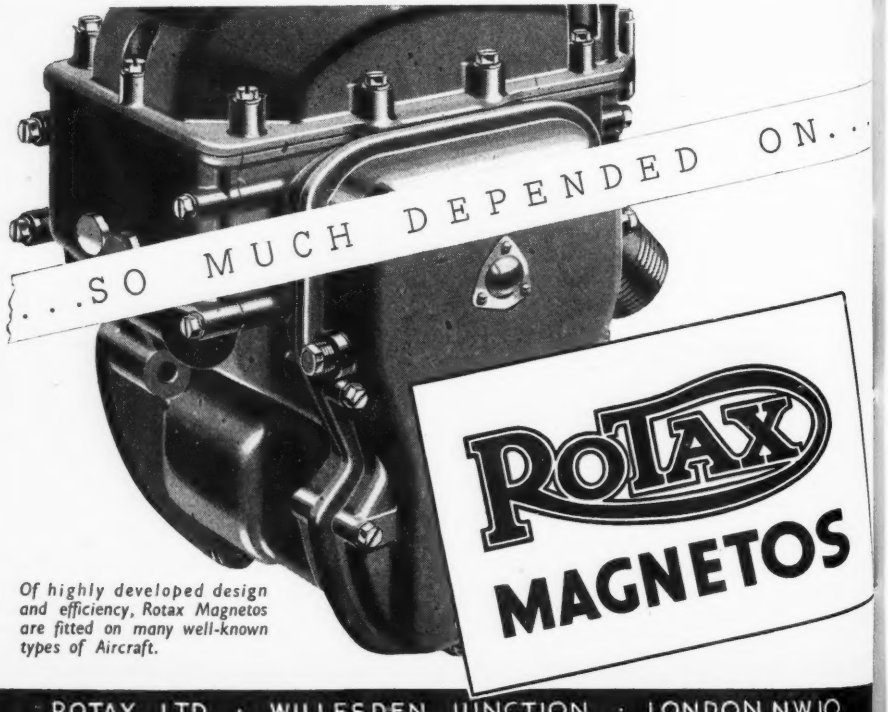

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AUGUST, 1943.

Library Opening.

The Library will be open on Saturday afternoons from 2.30 p.m. to 5.30 p.m., until further notice. A member of the Graduates' and Students' Committee will be in attendance, and the Library will continue to be open as long as the attendance justifies it.

Reprinting of the Durand Volumes on Aerodynamic Theory.

Durand's " Aerodynamic Theory " is being reprinted in a form which duplicates as nearly as possible the original size and binding. A committee which is composed of Dr. Theodore von Karman, Dr. Clark B. Millikan and Mr. E. W. Robischon, of the Aeronautics Department of the California Institute of Technology, has been organized to direct this non-profit venture. The cost is $30 per set. Arrangements can be made for anyone wanting a set to obtain them through the Society. Early application is advisable as only a limited number of sets will be available.

Death of Patrick Alexander.

By the death of Patrick Y. Alexander, on July 7th, 1943, the Society has not only lost one of its Founder Members, but British Aviation one of its early pioneers. Patrick Alexander was one of those men who gave his all to aviation when it was a very struggling and sickly affair, when everyone knew everyone else in the game, when most of those whose names are now household words were poor struggling enthusiasts.

Alexander built his first elastically driven model, based on Penaud's design, as long ago as 1878, and in the following year saw Giffard's balloon make its ascents at the International Exhibition in Paris. He was for many years a ballooning enthusiast and in 1894 made a parachute descent from a hot-air balloon. Three years before he had met the brothers Lilienthal and had many discussions on gliding with them.

By 1896 Alexander was widely known as one who was taking the keenest interest in the possibilities of flight and he was in close touch with such pioneers as Hiram Maxim, Octave Chanute, Langley, and others. In 1902 he met Orville and Wilbur Wright and, following that first successful flight in December, 1903, Alexander described their work to the Aeronautical Society. In 1911 he offered a prize of £1,000 for an aero-motor, won by the Green engine. With Mr. Griffith Brewer he collaborated in the publication of Aeronautics, an abridgement of the aeronautical specifications at the Patent Office from 1815 to 1891.

Alexander was a man who never hesitated to dip deeply into his own pocket to further the cause of aviation, though not always wisely. A man of wide interests, a great traveller, and above all a great enthusiast, his name will always be associated with those early pioneering days in this country, where

he had learnt, as so many others have since, that it is not necessary to be crazy to enter aviation—but it helps.

Acknowledgments.

The Council acknowledge with grateful thanks the gift of the following articles of historical interest:—

A Lunardi Balloon Plate, presented as a small tribute to the gallant Airmen of the Allies fighting in the Middle East, by Dr. F. J. Poynton, M.D., F.R.C.P.; a file containing designs and applications of Junkers Aircraft Jigs; British Patents Nos. 238, 212 and 238, 208, with the engines developed from these basic Patents, presented by Mr. H. R. Trost, B.Sc., A.M.I.Mech.E.; an antique basket fire from Dr. A. P. Thurston, F.R.Ae.S.

Changes of Address.

The attention of members is particularly called to the amount of work placed upon the heavily depleted staff by members who frequently change their addresses. It would considerably help the work of the office if members would give some permanent address to which Journals, etc., could be sent.

Owing to the extreme shortage of paper it will not be possible in the future to replace any Journals which have been lost in the post, due to such changes of address.

Elliott Memorial Prize.

The Elliott Memorial Prize has been awarded to Aircraft Apprentice J. D. Currell, who has obtained the highest marks in the General Studies Examination of the August, 1941, Entry of Aircraft Apprentices.

Election of Members.

The following members have recently been elected:—

Associate Fellows.—Philip Birch, Bruce John Bleach (from Graduate), Walter Alfred Clarke, Donald William Copley (from Graduate), William Harkness Dunn, Robert John Halford, Wilfred George Hicks, Frederick James Vernon Holmes, Kenneth Harris James, Leslie Arthur Lansdown, Albert Horace Manser, Stephan Mittler, Horace Edgar Owen, Guy Bryan Probert (from Graduate), William John Simons, Thomas Frederick Wyatt Smith, Kelvin Tallent Spencer, James Taylor (from Student).

Associates.—Lionel Maxwell Joachim Balfour, Charles Edward Atherton Causton, Lionel Wabon Samuel Collings, Roger Frederick Cordey, Norman Kempton Dyson, Horace John Forse, Basil Rowson Fossick, Kenneth Sidney Foster, Andrew Wauchope Fraser, Guy Henry Fuller, Arthur James Horace Hart (from Companion), Archibald Shaw Maclaren, Cyril Thomas Stedman Manser, James Douglas Murray (from Companion), Eric Richard Osler, Alexander Tauran Paterson, Cecil Wardman Poulter, Frank Thomas Reynolds, William George Ernest Rumble, Kethel Storm Russell, Joseph Smith, Henry Thompson, John Charles Walker, Horace George Westwood.

Graduates.—Richard George Bassett Burr, Robert Ellis Chapman, Dewi Manuel Davies, Ellis Vernon Fransman, Edward James Gregory, John Ernest Haines (from Student), John Tomlinson Howden, Maurice Edward Maxwell, James Garnett Sawyer (from Student), Stanley Bernard Simpson, Stanley Rodham Wigham.

Companions.—James Arthur D'Arcy Cartwright, John Herbert Condy, Charles Horace Cunniffe, Reginald Victor Longinotto, Harold James Lowings, Philip P. D. Pamplin-Green, Roy Kingsley Vandervord.

Students.—Ian Stewart Alexander, Timothy Egerton Herbert Beck, John Hugh Garth Bilney, Denzil Arthur Cheverton, Dorothy Helen Cooper, John Finnigan, Eustace Laurence Goldsmith, Frederick John William Harwood, Terence Patrick Hawkins, Tom Harker Morris, John Parr, Raymond Paskin, Anthony Arnold Seal, William Leonard Seaman, Ashley Ronald Tee, Margaret Mary Watts, Leslie Wookey.

Additions to Library.

Pamphlets in italics with location reference following in brackets.
Books marked * or ** may not be taken out on loan.

B.f.86.—*Birds versus Aeroplanes. By Frank W. Lane. "Everybody's Weekly," Nov. 28th,* 1942. (Y.10.b.8.)

*B.g.127.—Jane's All the World's Aircraft, 1942. Ed. by Leonard Bridgman. Sampson, Low and Marston. 1943. £3 3s. 0d.

*BB.d.31.—Junkers Bau-Vorrichtungen, England. (Designs and Applications of Junkers Aircraft Jigs: German mimeograph with photos. English typewritten translation, and copies of British Patents concerned.) 1939.

**BB.e.31.—Personal Diary of Visit to the U.S.A., Sept.-Oct., 1942. W. C. Devereux. (Privately printed.)

*D.a.A.20.—*Report on Air Transport. U.S. Office of War Information.* 1943. (PD.1/22.)

*D.a.C.19.—Civil Aviation, Canada: Summary of Monthly Reports, 1942. Dominion Bureau of Statistics, Ottawa. 1943.

*D.b.189.—*The Future of British Air Transport. Society of British Aircraft Constructors.* 1943. (PD.1/23.)

D.b.190.—Sky Ships. A. C. Hardy. Nicholson and Watson. 1943. 1/3.

D.b.191.—Air Transport (A Wartime Review of Peacetime Problems). Ed. by Ronald Walker. P. S. King and Staples, Ltd. 1943. 2/6.

D.b.192.—*K.L.M. West Indian Service Extension (to Miami, Florida). Press Release.* 1943. (Y.6.a.34.)

*D.d.18.—*The Education and Training of Aeronautical Engineers. (Reprint.) Royal Aeronautical Society.* 1943. (PE.2.b.11.)

D.e.35.—*International Air Transport: Planning. Political and Economic Planning (Broadsheet No. 208, June 29th,* 1943). (PD.2.b.6.)

*EE.b.70, 71.—*Ministry of Aircraft Production: Official Reports.* (Y.3.iii.17 and 18.)

Enemy Aircraft, Me. 109 and 110, He. 111P: Examination of Mercedes-Benz D.B. 601A engines, mountings and cooling system.

Enemy Aircraft, Me. 109E7 and 109F 1/2: Examination of Mercedes-Benz D.B. 601N and D.B. 601N1 engines and installation.

*EE.h.9.—Gas Turbines and Jet Propulsion for Aircraft (2nd Edition). G. Geoffrey Smith. Flight Publishing Co. 1943. 3/6. (First edition now released for loan.)

F.b.39.—Ethylene Glycol. Imperial Chemical Industries, Ltd. 1938.

*G.a.59.—Metallurgical Abstracts, Series II, Vol. 9, 1942. Institute of Metals. 1943.

I.a.33.—What is Mathematics? R. Courant and H. Robbins. Oxford University Press, New York. 1943. $5.

N.a.78.—Abstracts of Dissertations Approved for the Ph.D., M.Sc. and M.Litt. Degrees in the University of Cambridge (1941-42). University Press, Cambridge. 1943.

*Q.a.148.—*Science Library Bibliographical Series No. 590. Riveting, especially for Aircraft* (1936-1943). *(Stencil.) Science Museum*, 1943. (Y.9.B.)

*T.a.104.—*Grandfather of Flight (W. S. Henson). S. Paul Johnson. Article in "Technology Review," June,* 1943. (Y.5.H.)

T.b.84.—Speed! (Schneider Trophy Race). T. S. Denham. The Pilot Press. 1929.

TT.b.18.—The Bombing of Bruges. Paul Bewsher. Hodder and Stoughton. 1918. (Verse.)

*UC.7.—*Council for Scientific and Industrial Research, Australia. Translations*:—

No. 1. On a new Method of solving certain variational problems of Mathematical Physics. Walter Ritz. (J.f.d. reine u. angew. Mathematik, Vol. 135, 1909.)

*UU.c.—*National Advisory Committee for Aeronautics: Technical Memoranda*:—

No. 1044. Heat Transfer of Airfoils and Plates. Otto Seibert.

No. 1045. The Heat Transfer to a Plate in Flow at High Speed. E. Eckert and O. Drewitz. (From Forschung, May-June, 1940.)

No. 1049. Researches on Preliminary Chemical Reactions in Spark-Ignition Engines. E. Mühlner.

*WB.15/68.—Journal of the Institute of Metals, Vol. LXVIII, 1942.

*X.b.143, 144.—Air Transport and Civil Aviation Yearbooks. Cunliffe-Owen Aircraft, Ltd. Todd Publishing Co. 1943 (Two copies.)

J. LAURENCE PRITCHARD, *Secretary and Editor.*

INTRODUCTION TO THE THEORY OF PHOTOELASTICITY AND ITS APPLICATION TO PROBLEMS OF STRESS ANALYSIS.

By R. E. Arthur, B.Sc.

1. Introduction.

Many problems arise in stress analysis which are not reasonably susceptible to mathematical treatment. Recourse may then be had to experimental methods. One of the most useful of these is the photoelastic method. This method is based upon the fact that transparent materials when stressed undergo changes in their optical properties which can be measured and related to the applied stress.

The experimental procedure consists of making a transparent model of the structure being analysed. The model is loaded similarly to the prototype and the resulting optical effects examined. The optical arrangement used for this examination is called a polariscope. This consists essentially of a polariser and an analyser between which the model is placed. When light is passed through the arrangement and the model viewed through the analyser the former exhibits light and dark fringes, the pattern of which depends upon the stress distribution in the model.

There are two polariscopes, viz., the plane polariscope and the circular polariscope. In addition to these there is the photoelastic interferometer. The object of the present paper is to give, with the aid of illustrations, a clear physical picture of these instruments. To do this it is necessary to consider the nature of light.

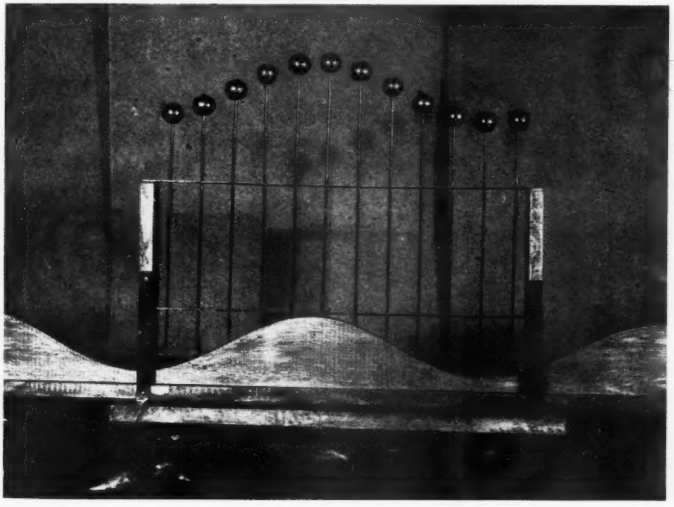


Fig. 1.

Apparatus for demonstrating the propagation of a transverse wave.

2. The Nature of Light.

The subject is adequately covered by the Electromagnetic Wave Theory of Light. Here light is identified with electromagnetic radiation, the most familiar example of which is wireless waves. This radiation is considered to travel through space as a transverse wave. The nature of such a wave can be understood by reference to the apparatus shown in Fig. 1. The balls here follow the contour of the " switchback " slide as the latter is moved backwards or forwards. It should be noted that the rods on which the balls are mounted can move only upwards and downwards and not backwards and forwards. This demonstrates an essential property of the transverse wave, viz., although the wave moves through the balls, the latter themselves do not progress. Such a wave which continues to vibrate in one plane is said to be plane polarised. Normally light waves in free space are not polarised and to render them so it is necessary to pass them through a crystal such as calcite in the form of a Nicol prism.

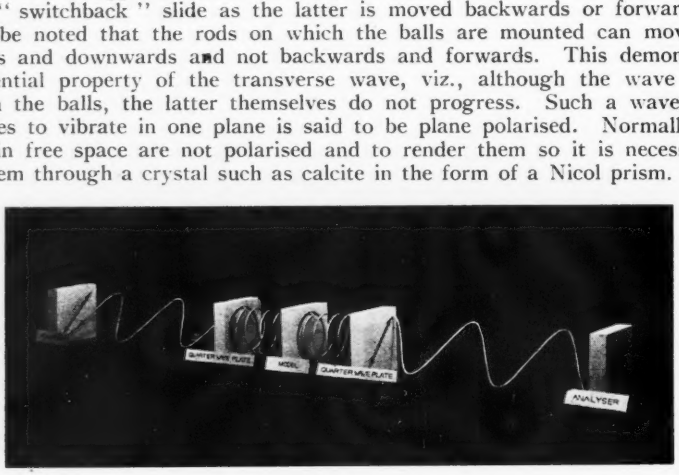


Fig. 2.
The circular polariscope.

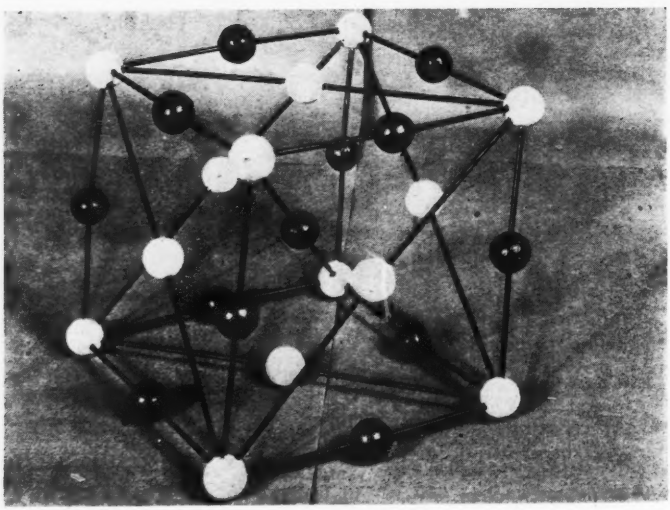


Fig. 3.
The atomic structure of calcite.
Calcium atom is white.
Carbon atom is black.
Oxygen atoms are omitted for clearness.

3. THE NICOL PRISM.

The shape of the Nicol can be appreciated from Fig. 4 and the plane of the vibrations it transmits are indicated by the double arrow on the end face. When unpolarised light strikes an end face it enters the crystal as two separate plane polarised waves whose separate vibrations are mutually perpendicular. If allowed to pass out of the crystal by the far end these waves continue to travel as two mutually perpendicular plane polarised waves. To " trap " one of the waves the calcite crystal is divided and cemented together again with Canada balsam, as shown in the photograph Fig. 4. This results in the wave whose vibrations are perpendicular to the arrow being reflected at the joint and passing out at the two bottom long faces of the prism. The atomic structure of calcite ($CaCO_3$) is shown in Fig. 3, whilst its identity with the shape of the Nicol prism is shown in Fig. 5. The line joining the top near atom to the bottom distant atom is called the optic axis of the crystal. The plane of vibration of the transmitted wave contains the optic axis and is therefore called the plane of the optic axis. This Nicol prism is called the polariser.

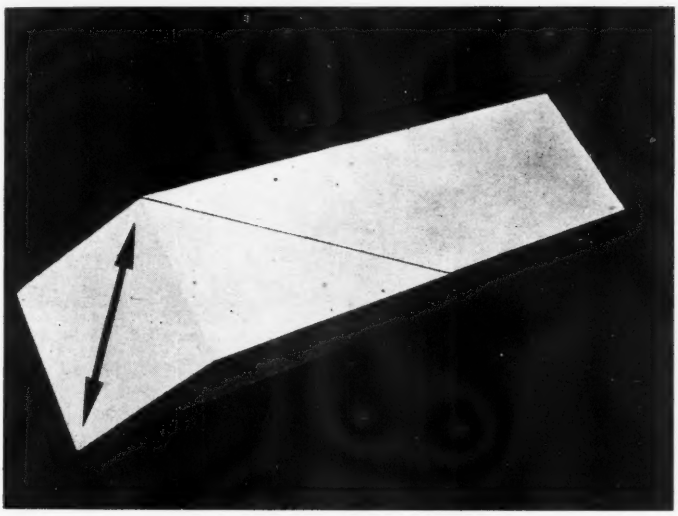


FIG 4.

The Nicol prism showing the plane of the transmitted vibrations.

4. THE PLANE AND CIRCULAR POLARISCOPES.

When a plane polarised wave has been produced by a polariser it can only be recognised by using a second Nicol prism called an analyser. The explanation of this is as follows. Any Nicol and in particular the analyser can transmit only those waves whose vibrations are parallel to the plane of the optic axis. Thus if the vibrations coming from the first Nicol or polariser are perpendicular to the plane of the optic axis of the second Nicol or analyser then no light gets through the latter. Such a combination of Nicols is called a plane polariscope. Its use will be considered later when the production of isoclinics is discussed.

A second type of polariscope used in photoelasticity is the circular polariscope, a model of which is shown in Fig. 2. The functioning of this type of polariscope will now be considered.

By passing the plane polarised light emerging from the polarising Nicol through a plate of quartz crystal of suitable thickness and orientation the light vector instead of remaining in one plane and varying in magnitude, remains constant whilst its tip follows a spiral path. Such light is said to be circularly polarised. On passing this light through a second plate of quartz of equal thickness to the first and suitably orientated it can be converted back to plane polarised light which can then be examined by the analysing Nicol. The circular polariscope is used for the production of Isochromatics, which will be explained later.

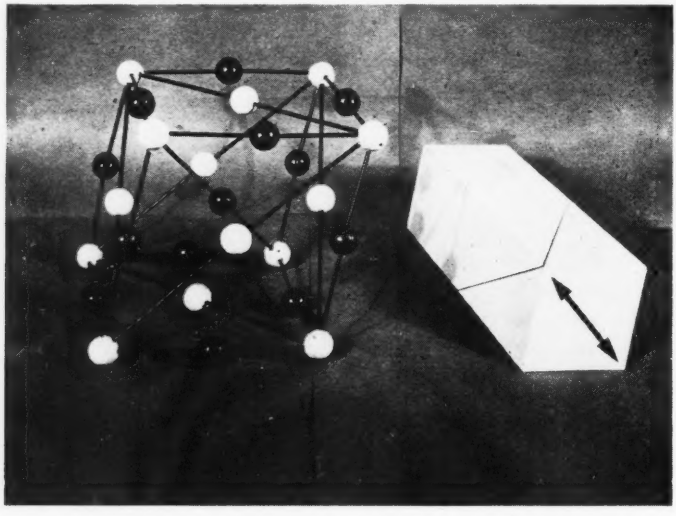
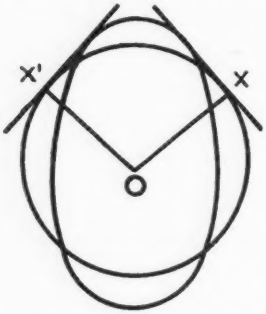


FIG. 5.

The identity of the atomic structure and shape of the Nicol prism.

5. THE PROPAGATION OF LIGHT IN A CRYSTAL. DOUBLE REFRACTION.

Before the use of the polariscope can be understood it is necessary to study how light radiates through a crystal. In isotropic media and cubic crystals the light waves spread out spherically. In general, however, the light spreads out on two surfaces, the shapes of which are shown in the model photographed in Fig. 6. For clearness the inner surface is shown complete whilst the outer surface is represented by its principal sections. The radii OX and OX', which are perpendicular to the common tangents to the two surfaces, are known as the optic axes of the crystal. As there are two such axes the crystal is termed a biaxial one. The study of biaxial crystals need not concern us further and we shall pass on to the consideration of the special cases where the optic axes are coincident and the crystal becomes uniaxial. When the radius of the circular section equals the semi-major axis of the ellipse the surfaces reduce to an ellipsoid inside a sphere. A crystal having these shapes for its ray velocity surfaces is called a positive uniaxial crystal. The surfaces are represented in Fig. 7. If the radius of the circle is equal to the semi-minor axis of the ellipse the surfaces become



a sphere inside an ellipsoid. A crystal having these shapes for its ray velocity surfaces is called a negative crystal. These surfaces are represented in Fig. 8. In both cases the line joining the points of coincidence of the two sheets forming the ray velocity surface is the optic axis.

The splitting up of the incident light wave into two separate sheets travelling with different velocities is called double refraction. Furthermore, the vibrations in the two sheets are mutually perpendicular. The wave spreading out as a spherical sheet is called the ordinary wave and the one spreading out as an ellipsoid the extraordinary. For the biaxial crystal both waves are extraordinary as neither spreads spherically.

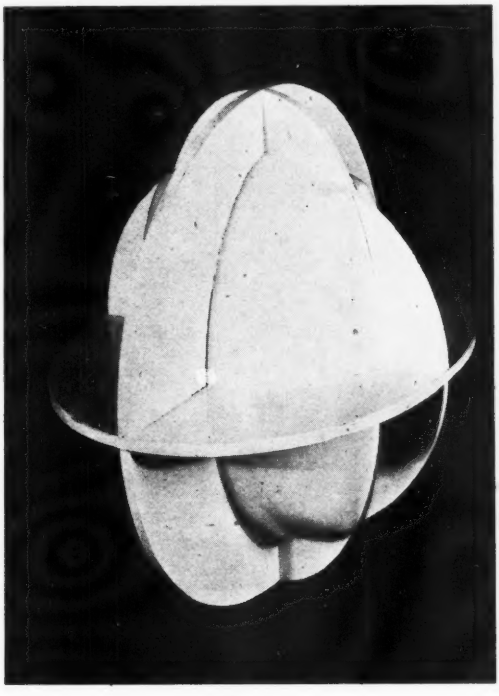


FIG. 6.

The ray velocity surface for a biaxial crystal.

6. ARTIFICIAL DOUBLE REFRACTION PRODUCED BY STRAIN.

So far we have considered the propagation of light in crystals. However, isotropic media such as glass and transparent plastics become doubly refracting when strained. The optic axes of such " artificial crystals " are parallel to the direction of applied stress. An isotropic medium in tension behaves as a positive uniaxial and in compression as a negative uniaxial crystal. Figs. 9 and 10 show the directions of the optic axes, the sections of the ray velocity surface and the directions of the vibrations of the light vectors for specimens under plane tensile and compressive stresses. It is evident from the photographs that the two light vectors travel with different velocities. In the case of the positive crystal the ordinary wave travels faster than the extraordinary wave. The reverse is true for the negative crystal. All light, whether polarised or not, on entering the crystal is resolved into two plane polarised waves vibrating parallel and perpen-

dicular to the optic axis. If the light emerging from the polariser of the polariscope strikes the specimen and the plane of polarisation is parallel or perpendicular to the optic axis of the latter the wave will be transmitted without modification and so can be extinguished by the analyser of the polariscope. For any other orientation of the plane of the wave striking the specimen or model the light will be resolved into two plane waves lying, as already stated, parallel and perpendicular to the optic axis of the model and so no position of the analysing Nicol will intercept both waves simultaneously and thus some light passes through the analyser to the eye.

7. Isoclinics. Measurement of Principal Stress Directions.

The directions of the two light vectors emerging from the model can be identified with the directions of the principal stresses at the point of emergence.

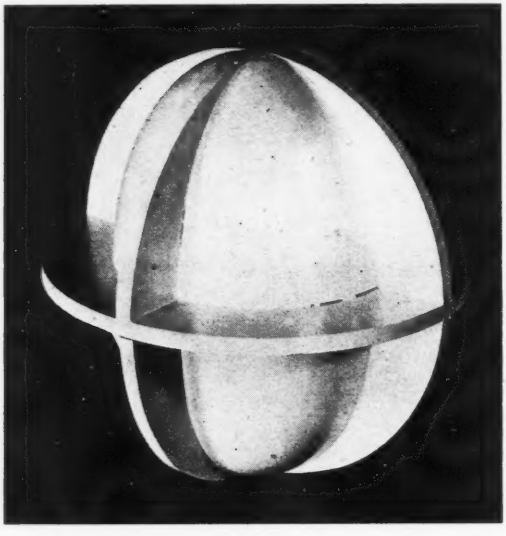


Fig. 7.
The ray velocity surface for a positive uniaxial crystal.

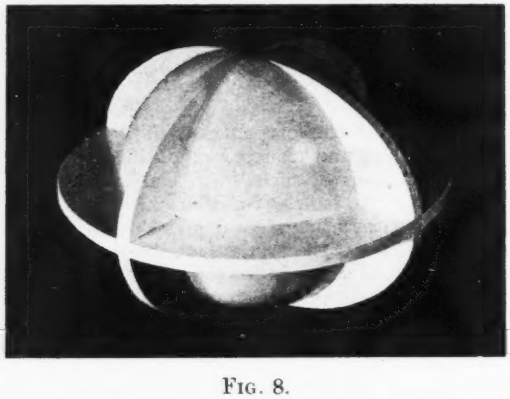


Fig. 8.
The ray velocity surface for a negative uniaxial crystal.

Thus the polariscope affords a method of determining the directions of the principal stresses at all points on the model. To do this the polarising and analysing Nicols are rotated together until the point of the model under observation appears black. For this position the long diagonal of the end face of the analyser indicates one of the directions of principal stress at the point of the model under observation. The direction of the second principal stress will be perpendicular to this or parallel to the shorter diagonal of the end face of the

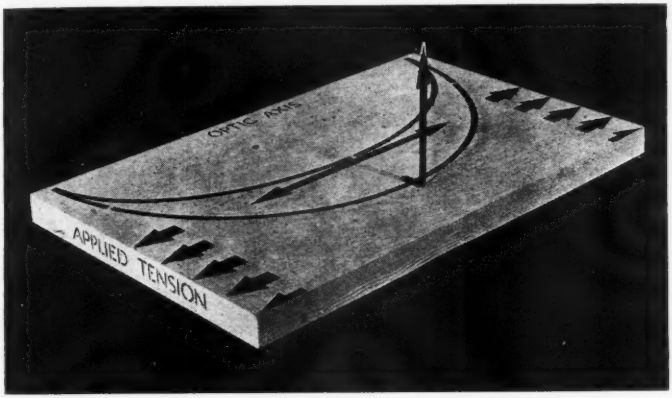


FIG. 9.
The propagation of the ordinary and extraordinary waves in a tensile model.

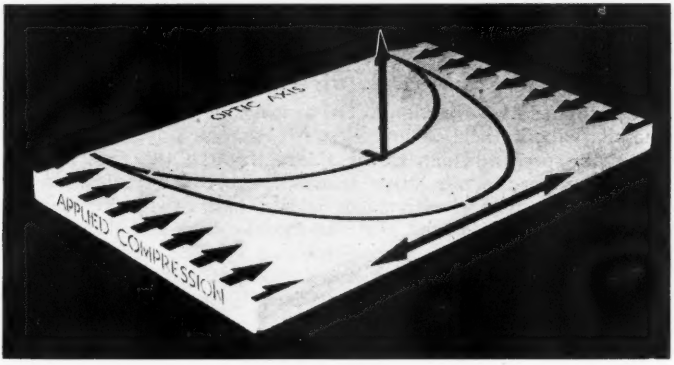


FIG. 10.
The propagation of the ordinary and extraordinary waves in a compression model.

analysing Nicol indicated by the vector in Fig. 4. For this adjustment of the polariscope all points on the model having the same principal stress directions will appear black when viewed through the analyser of the polariscope. The pattern consists of dark contour lines on a bright background, the lines joining all points on the model having the same principal stress directions. If the polarising and analysing Nicols are simultaneously rotated into a new position

the combination will automatically select another set of points for which the principal stress directions are determined by the position of the Nicols as explained above. Thus the pattern of the fringes seen depends upon the orientation or inclination of the Nicols and hence the significance of the term isoclinics used to describe these fringes, *i.e.*, contours joining all points having the same principal stress directions.

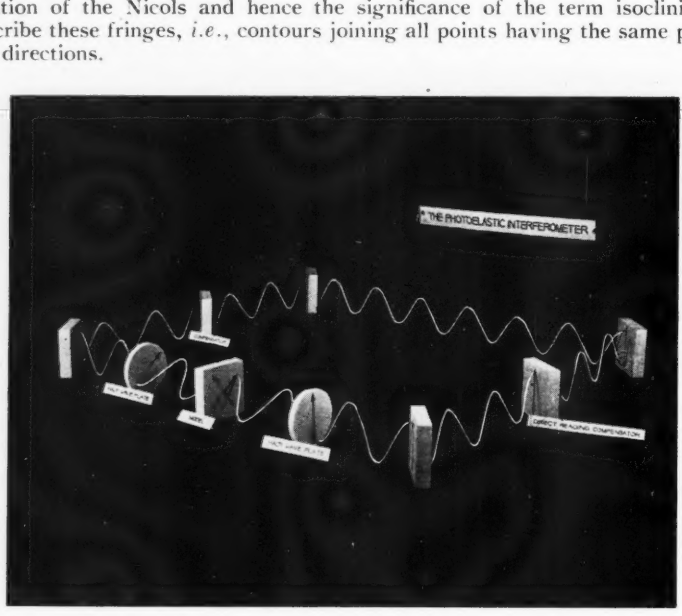


FIG. 11.
The photoelastic interferometer.

8. ISOCHROMATICS. MEASUREMENT OF DIFFERENCE OF PRINCIPAL STRESSES.

Having determined the directions of the principal stresses it now remains to learn something about their magnitudes. It has already been mentioned that the two mutually perpendicular waves travel through the model with different velocities so that there is a relative retardation between the two waves. This retardation increases with the time for which the waves have been travelling, *i.e.*, it depends upon the thickness of the model. The retardation also depends upon the principal stress difference. This for a given thickness of model the retardation is proportional to the principal stress difference at the point of the model under investigation. If plane polarised light from the polarising Nicol is inclined to the directions of principal stress it will, on entering the model, be resolved into two plane waves parallel to the latter directions. The relative retardation between the two waves increases as the waves pass on through the crystal and the state of polarisation of the emergent composite wave depends upon this relative retardation upon emergence. The action of the quarter wave and half wave plates depends upon this relative retardation between the component waves. In the case of the quarter wave plate one component falls behind the other by a quarter of a wave. On recombining, therefore, the resultant vibration is circularly polarised. If the plate produces a retardation of a half wave between the two components the resultant emergent vibration will be plane polarised, the planes of polarisation of the incident and emergent vibrations being equally and oppositely inclined to the plane of the optic axis. If by then one wave train has fallen behind by one wavelength the emergent composite wave

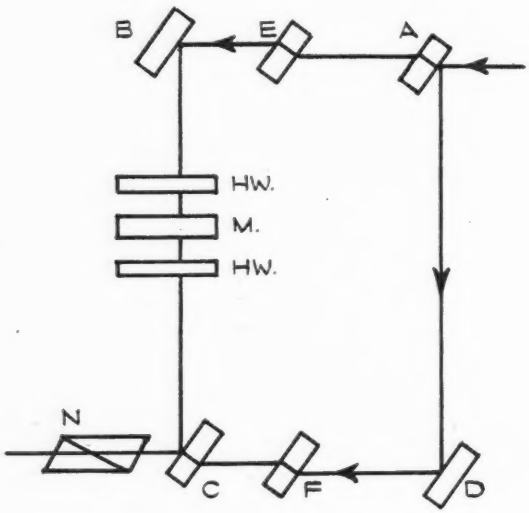
will be polarised in its original plane and the analysing Nicol will intercept the light. Thus the point on the model being viewed will be black. So for all points for which the relative retardation is one or more whole wavelengths the plane of polarisation of the emergent wave will be the same and all such points will appear black. The dark fringe contours connecting points of equal retardation are called isochromatics. If these isochromatics are viewed in the plane polariscope there will be isoclinics superimposed and it is impossible to distinguish them. To overcome this difficulty the circular polariscope is used for viewing isochromatics alone. There can now be no isoclinics due to the non-directional character of circularly polarised light. Only at those points on the model for which the relative retardation is a whole number of wavelengths will the emergent light be circularly polarised which can be cut off by the analysing quartz plate and Nicol prism. The fringes belong to various orders, the order being equal to the number of wavelengths retardation between the two interfering waves. The principal stress difference at any point is indicated by the order of the fringe at that point. To identify the fringe of zero order white light is used in place of monochromatic. The zero fringe will then be black while the others will be highly coloured. For more precise measurements a calibrated compensator is used to compensate for the relative retardation produced in the model itself. This gives a direct reading of the principal stress difference at the point of the model in question. The compensator is of the Babinet type. By this method the separate principal stresses can be determined only when one has been determined from other considerations. Alternatively the sum of the principal stresses can be determined by the isopachic method which has nothing to do with photoelasticity and will not therefore be discussed.

9. The Photoelastic Interferometer. Measurement of Principal Stresses Separately and Their Directions.

The Photoelastic Interferometer affords a method of determining both the directions and separate magnitudes of the principal stresses. A model of this apparatus is shown in Fig. 11.

The apparatus consists of four optical parallels, A, E, C and F and two optical flats B and D. Polarised light whose vector is perpendicular to the plane of the paper is divided at A into a transmitted wave following the path $AEBC$ and a reflected wave following the path $ADFC$. After reflection at C the wave $AEBC$ interferes with the wave $ADFC$ to produce a set of interference fringes. If one of these waves is retarded this will result in a sideways shift of the fringes. The photoelastic model M under investigation is placed in the path of the wave $AEBC$. In order to investigate the stress at each point in the model all the monochromatic light passing through the interferometer must be focussed on the point. This is done by having a point source and a suitable optical system to produce an image of this source on the model. The model can be mounted in a suitable frame so that this image can be brought on to any point at which the stress is to be measured. For the plane polarised wave to pass through the model as a single wave its orientation must be parallel to one of the principal stress directions at the point of incidence on the model. These directions vary from point to point in the model. In order to adjust the orientation of the plane of the vibrations in the wave, half-wave plates HW are interposed on either side of the model. The first plate can be rotated until it brings the plane of the wave leaving it parallel to one of the principal stress directions in the model. Having passed through the model the plane of the wave is brought back to its original orientation by a second half-wave plate which counteracts the rotation produced by the first plate. Actually the two half-wave plates are connected so as to be capable of simultaneous rotation. The section of the wave train between the two half-wave plates rotates through twice the angle through which

the plates themselves rotate. Thus the directions of the principal stresses can be found from the position of the half-wave plates. When carrying out the above the wave $ADFC$ is cut out so that no fringes are visible, the whole field appearing uniformly illuminated. An analysing Nicol N is set to intercept the waves traversing the path $AEBC$ without the model in position. When this has been done the model is placed between the half-wave plates and the latter rotated until extinction of the light occurs.



Having found the directions of the principal stresses it now remains to determine their separate magnitudes. To do this the analysing Nicol and the shutter cutting off the wave $ADFC$ are removed, thus rendering the interference fringes visible again. If the model is now subjected to increasing stress the fringes commence to pass across the field of view and the individual principal stress being measured is a linear function of the fringe displacement. It is not necessary, however, to count the number of fringes passing across a given point of the field as a direct reading compensator F, shown in the sketch and also in the photograph Fig. 11, placed in the path of the wave $ADFC$ can be continually adjusted to compensate for the increasing retardation of the wave $AEBC$ passing through the model M as the latter is subjected to increasing stress. The adjustment being to keep the fringes in a fixed position instead of allowing them to cross the field.

10. Conclusion.

No attempt is made in this article to describe the details of technique of photoelasticity, as these are adequately treated in the individual papers on any particular problem. These descriptions of technique are meaningless unless the fundamentals of the subject are properly grasped. The specialist takes for granted conceptions which are by no means easy for a non-specialist in the subject. Most attempts to teach these conceptions rely on descriptions rather than the visual method. If the reader is shown a picture or model wherever possible there is less risk of misunderstanding. It is to satisfy this consideration that this paper is considerably supplemented with photographs of models which it is hoped will make understanding easier for the reader.

ASTRONOMICAL NAVIGATION WITHOUT MATHEMATICS

By Lt.-Col. A. L. Mieville, D.S.O., M.C., M.I.Mech.E., M.E.I.C.

Introduction.

Multitudes of young men are starting to study navigation. As a rule it is only after many months of painful work that they come to see what it is all about —many of them never get to that point at all.

In none of the books on navigation have I been able to find a simple picture, defining each step in the reasoning that enables us to navigate by the stars. Hence this effort. As set out here the principles can be grasped by anyone.

There is nothing new or secret in the matter. It is only a reduction to its simplest form of what is generally supposed to be a very complicated subject.

The method was used in 1914, later by Alcock and Brown, and others. More recently, Captain Weems, of U.S. Navy, published his charts which have been in regular use for flying.

The principles are the same as those upon which the usual mathematical methods are based, but in this method there are no logarithms, no mathematics, no formulæ, no difficulties—a relief to the navigator who usually must solve spherical triangles, often under appalling conditions.

The article is not only a general statement of principles but a precise method by which navigation has been and is now being carried on. I believe it will be developed rapidly now that its simplicity, speed and freedom from the danger of error are becoming more appreciated.

Half an hour's study of this article would show the student that the subject is really simple; then being predisposed to find it so and having already got hold of the why and wherefore of the mathematical processes (which must still be learnt for other branches of the subject) he would get through his work much more quickly.

It would form an invaluable background to which the student would constantly refer when in difficulties and would rob the subject of all its terrors. Our output of navigators would be speeded up—this is of the utmost national importance.

Foreword.

In the air, at sea, in the desert, our job as navigators is to find out where we are. Provided that we can see two known stars we can find our "position" by the following method without elaborate calculations.

The Earth.

Suppose we tie a string to the top of a flagstaff and that we walk in a circle round the base of the flagstaff keeping the base of the flagstaff as the centre of the circle, holding the string taut.

The angle formed by the string and the horizontal or ground level is what is called in navigation the "altitude" of the top of the flagstaff. Suppose it to be 70 degrees in this case.

The string will always make the same angle or "altitude," 70 degrees with the horizontal, so long as we keep walking on the same circle. In other words the "altitude" of the top of the flagstaff is the same 70 degrees from any point on the circumference of that circle and it cannot be 70 degrees from anywhere else upon the whole earth. Let us mark that circle 70 degrees in Fig. 1 (lower view).

Now suppose we walk on a larger circle round the base of the flagstaff. The angle formed by the string and the horizontal will now be smaller than before. Suppose it to be 60 degrees. That angle or " altitude " will be the same 60 degrees wherever we are, provided we keep somewhere upon the circumference of that second circle, and it cannot be 60 degrees from anywhere else upon the whole earth. Let us mark that circle 60 degrees in Fig. 2 (lower view).

Suppose we walk in a still larger circle round the base of the flagstaff. The angle formed by the string and the horizontal will now be still smaller, say 50 degrees and that angle or " altitude " will be the same 50 degrees wherever we are, provided we keep somewhere on the circumference of that third circle, and it cannot be 50 degrees from anywhere else upon the whole earth. Let us mark that circle 50 degrees in Fig. 3 (lower view). In other words, the " altitude "

FIG. 1.

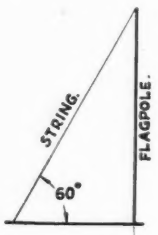


FIG. 2.

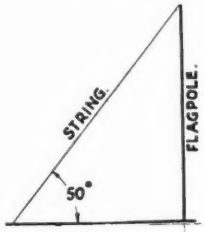
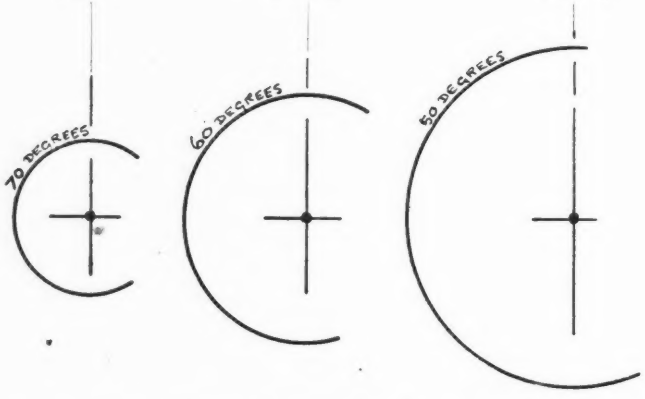


FIG. 3.



of the top of the flagstaff remains the same provided we remain on some one circle of which the flagstaff is the centre. If we walk on a larger circle the angle or " altitude " gets less, and so on.

Let us combine Figs. 1, 2 and 3 and produce Fig. 4 thus:—

Let the place where the flagstaff enters the ground be marked A. Take A as centre and describe a circle of the same size as in Fig. 1 and mark it 70 degrees. Again with A as centre describe a second circle, of the same size as in Fig. 2, and mark it 60 degrees. Again with A as centre describe a third circle of the same size as in Fig. 3 and mark it 50 degrees. If we went out for a walk and took an observation of the top of the flagstaff and found the angle or " altitude " to be 60 degrees: by using Fig. 4 as a map we would know that we must be on the 60 degrees circle.

Suppose now there were a second flagstaff B somewhere near the first flagstaff A. Just as we have done with flagstaff A, we establish a series of circles upon

the earth but with the base of flagstaff B as centre. We would get a figure very much like Fig. 4, except that we have flagstaff B at the centre instead of flagstaff A.

Suppose the two flagstaffs to be fairly near together: we would get something like Fig. 5.

Now, if during our walk we stop and by means of a suitable instrument take an observation for the " altitude " of the top of A and find it to be 60 degrees, we must be upon the 60 degrees circle.

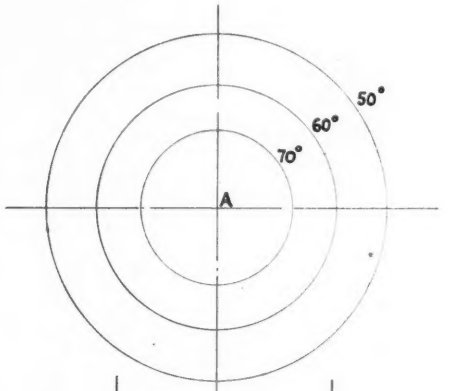


FIG. 4.

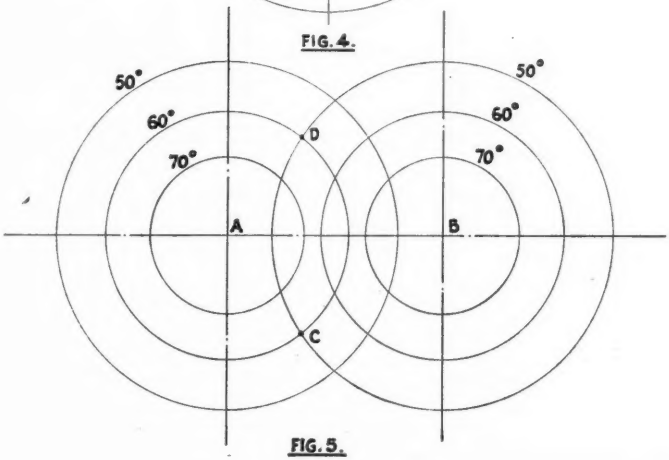


FIG. 5.

If, without moving our position, we take another observation for the " altitude " of the top of the flagstaff B and find it to be 50 degrees, we know that we must be upon the 50 degrees circle of flagstaff B.

But we are already upon the 60 degrees circle of flagstaff A.

Since the 50 degrees circle of flagstaff B cuts the 60 degrees circle of flagstaff A at only two points, C and D, we must be at one or other of those two points, for C and D are the only two points on the whole earth from which the "altitude" of flagstaff A is 60 degrees while at the same time the " altitude " of flagstaff B is 50 degrees. If we know that we are, say, below the line going from A to B, we know that we can only be at the point C. In other words we have found our " cut " or " position " C.

Evidently, we might with A as a centre draw upon the earth a series of these "position" circles to suit any series of altitudes we like to choose. Similarly we could do this with B as centre. In Fig. 6 we have done this.

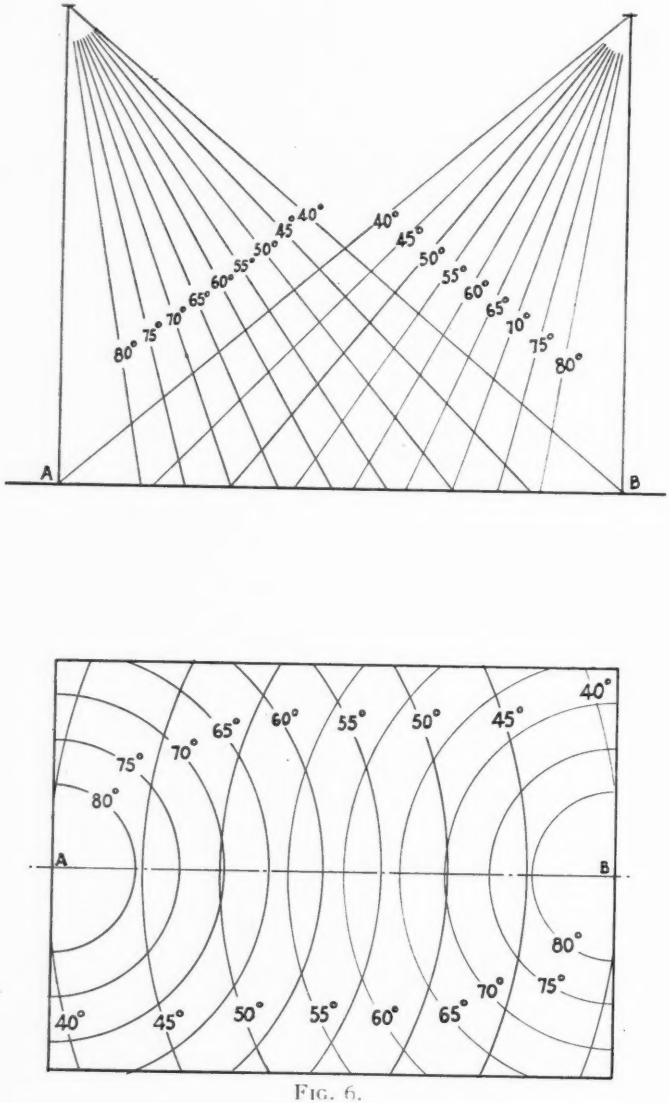


FIG. 6.

Here the circles are numbered 80, 75, 70, 65, 60, 55, 50, 45, etc. The altitude of the top of a flagstaff is taken from any point on its 50 degrees circle would be 50 degrees, and so on.

If our flagstaffs were so tall as to be visible from great distances, and if a series of them with distinguishing marks were set up all over the earth it would be possible to find our position at any time by taking altitude observations upon any two flagstaffs which were recognisable. This is really what we are doing when we use the stars for navigation.

The Stars.

We must now consider the stars.

We may take the stars as being fixed upon an enormous transparent sphere which surrounds the earth. This globe is called the Celestial Sphere. The centre of our earth is also the centre of this Celestial Sphere (see Fig. 7).

It should first be made clear that the stars are not moving about amongst themselves but are definitely fixed upon the Celestial Sphere. Most of us know that they are fixed for we recognise certain of the well known constellations or groups of stars by their shape and position relative to one another. If their shape or position altered we would be unable to recognise them.

There are maps showing the positions of all the stars in relation to one another upon the Celestial Sphere. The stars then are in fixed positions on the Celestial Sphere just as the cities and towns are fixed upon the earth. The movement that we see taking place is that of the whole earth, which with its cities, towns, etc., fixed upon it, rotates. The Celestial Sphere within which the earth is spinning stands still with its stars in fixed positions upon it.

The Earth and the Celestial Sphere.

Latitude and longitude.

If we look at a globe of the earth we see that it is covered by a regular network or grid of lines (Fig. 8).

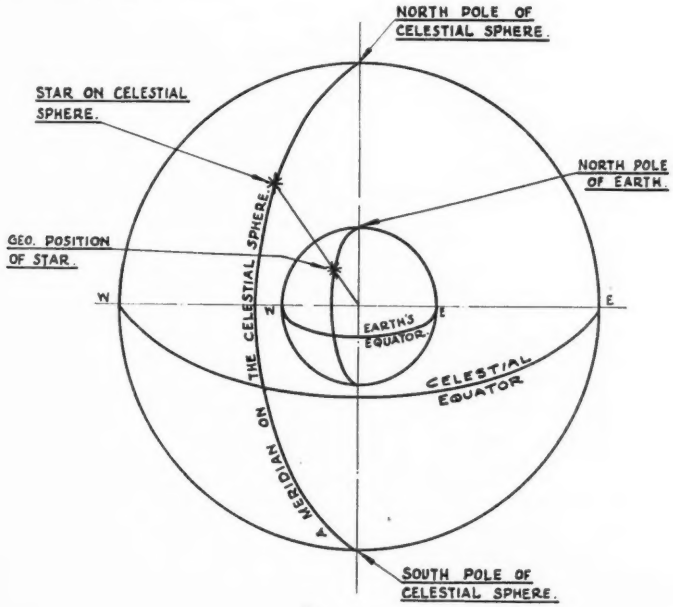
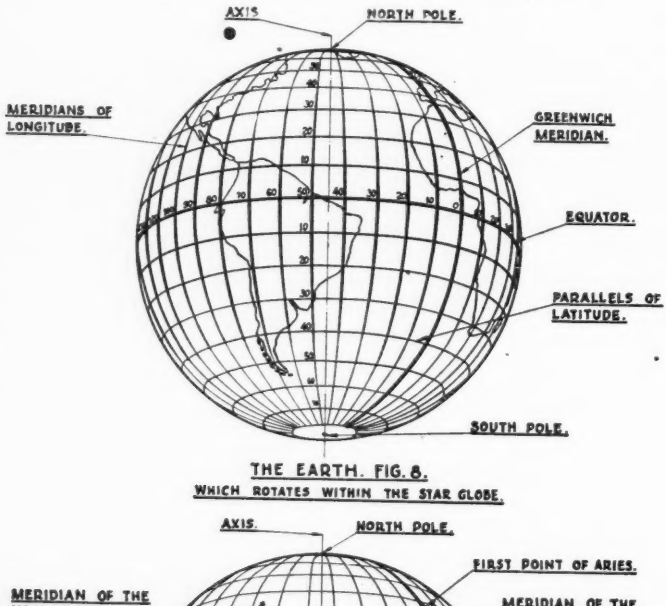


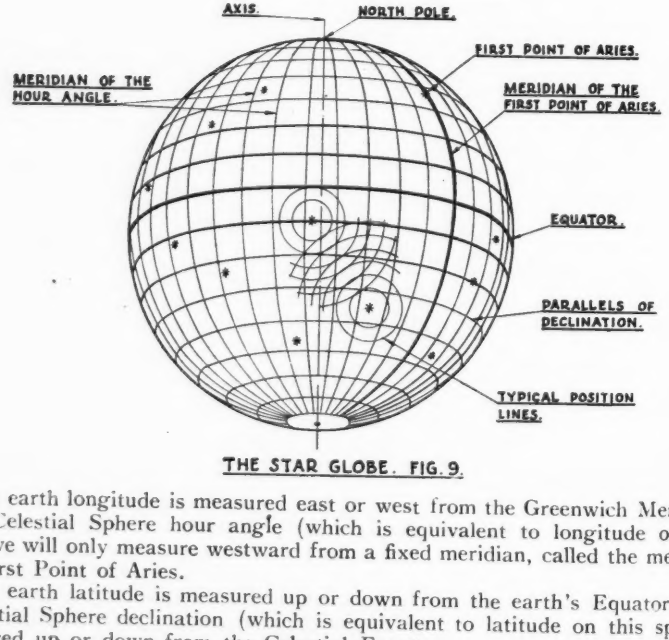
Fig. 7.

The Celestial Sphere.

Parallels of latitude which are the lines parallel to the Equator. Meridians of longitude which are the lines running from Pole to Pole. We describe the position of a point on the surface of the earth or sea by stating its latitude and longitude. The Celestial Sphere may also be covered with a similar network of lines or grid, but latitude we call " declination " on the Celestial Sphere ; longitude we will call " hour angle " on the Celestial Sphere (Fig. 7).



THE EARTH. FIG. 8.
WHICH ROTATES WITHIN THE STAR GLOBE.



THE STAR GLOBE. FIG. 9.

On the earth longitude is measured east or west from the Greenwich Meridian. On the Celestial Sphere hour angle (which is equivalent to longitude on this sphere) we will only measure westward from a fixed meridian, called the meridian of the First Point of Aries.

On the earth latitude is measured up or down from the earth's Equator. On the Celestial Sphere declination (which is equivalent to latitude on this sphere) is measured up or down from the Celestial Equator.

New York, say, is about 75 degrees west of Greenwich or 75 degrees W. long., and about 40 degrees north of the Equator, or 40 degrees N. latitude.

Similarly the position of a star X may be given as 75 degrees west of First Point of Aries, 40 degrees N. declination.

THE CONNECTION BETWEEN THE EARTH AND THE STARS.

Let us now imagine the earth to be stationary. The stars would then not only be fixed in relation to one another as they are upon the Celestial Sphere, but would also be fixed in relation to the earth. Imagine our flagstaff to be so long that it starts from the centre of this fixed earth and reaches the stars. Imagine that each star is stuck like a knob on the top of a flagstaff which goes straight from the centre of the earth up to the star. The point where such a flagstaff pierces the earth is called the geographical position or " geo-position " of the star (Fig. 7).

We can now proceed much as we did with our original flagstaff and with the base or geo-position of the star's flagstaff as a centre describe a series of " position " circles on the earth. Better still if we had a transparent celluloid cover or globe that fitted smoothly and closely over the earth itself, we could mark upon this cover the geo-position of the star. We might do this with each of the chief stars given in the Air Almanac. We would then have a transparent globe (Fig. 9) fitting closely on the earth globe and with the geo-position of each of the chief stars marked upon it. Let us call this the " Star Globe " (Fig. 9).

With the geo-position of each star as centre we could describe a series of " position " circles upon our transparent " Star Globe " just as we did around each of our flagstaffs (Fig. 9).

Upon the transparent " Star Globe " we could also describe the meridian of " The First Point of Aries " equivalent to the Greenwich meridian, also other meridians just as is done upon the earth globe. We could also describe upon the transparent " Star Globe " parallels of declination equivalent to the parallels of latitude on the earth globe (Figs. 8 and 9).

Now imagine a long rod or axle or " axis " passing through the North and South Poles of the earth globe and on through the transparent " Star Globe " upon which the geo-positions of the stars have been marked. Where this axis pierces the " Star Globe " will be the geo-positions of the North and South Poles of the Celestial Sphere (Fig. 9).

The two globes are now mounted upon the same axle or axis. If the transparent " Star Globe " be now held fixed the inner or earth globe can be turned round upon the axle which is common to both globes.

This represents what is happening continually, viz., the earth is rotating on its axis, the stars on the Celestial Sphere surrounding the earth stand still.

The transparent " Star Globe " is now just like the earth globe, having parallels of declination equivalent to the parallels of latitude and meridians of star longitude or hour angle equivalent to those of the earth's longitude described upon the earth globe.

The North and South Poles of the star globe exactly conform with the North and South Poles of the earth globe. The Equator on the star globe exactly conforms with the Equator on the earth globe and so on (Figs. 8 and 9).

Upon this transparent star globe we have also located the geo-position of the North and South Celestial Poles and of the most easily visible stars. Round the geo-position of each star has been described upon this transparent star globe a series of " position " circles much as shown in Fig. 6.

Now if we go for our walk with our star globe as a map we have only to take altitude observations of any two convenient stars and we find our position upon

this outer or star globe. But what we want to do is to find our position upon the earth globe.

If the earth globe were not rotating within the star globe our position upon the earth would have been found already, for our meridians of hour angle would be the same as the meridians of longitude upon the earth.

Now as the earth globe revolves upon its axis within the star globe every point upon the star globe (which is stationary) will trace out a circle upon the earth globe beneath it and all such circles will be parallel to the Equator and will in fact be parallels of latitude. Thus we see that the " position " already found upon the star globe will trace out its own parallel of latitude on the earth globe beneath it. In fact our declination upon the star globe is our latitude upon the earth globe.

For example, if the declination of our " cut " or " position " as found upon the star globe be 40 degrees north of the Equator, our latitude upon the earth globe will also be 40 degrees north of the Equator.

So we have found our latitude. We have yet to find our longitude.

Time.

The longitude of our position on the earth globe depends upon how far the earth had revolved within the star globe when we made our observations, that is to say, upon the time.

Actually the earth turns round upon its axis and makes one complete revolution of 360 degrees every 24 hours. The Celestial Sphere, surrounding the earth, stands still. Our transparent star globe (Fig. 9), which represents the Celestial Sphere so conveniently, also stands still.

Draw a line upon the earth globe to represent the Greenwich meridian (Fig. 8). Draw a similar line upon the star globe to represent the meridian of the First Point of Aries (Fig. 9).

As the earth revolves the Greenwich meridian passes directly under the meridian of the First Point of Aries on the star globe, sweeps on round the full circle of 360 degrees, passes beneath all the other stars in turn, finally passing beneath the meridian of the F.P. of A again, and so on. (F.P. of A. is short for First Point of Aries.)

This goes on continually.

The Greenwich meridian then is like the hand of a clock, and time may be taken as the angle that has been swept out by the Greenwich meridian since last it passed directly beneath the F.P. of A.

Navigators carry a very accurate clock or chronometer. From this they can tell the time or how long it was since the Greenwich meridian last passed the meridian of the F.P. of A.

Our Position Found.

We have already fixed our position upon the star globe. Now, without moving the star globe, rotate the earth globe within it until the angle between the Greenwich meridian on the earth globe and the meridian of the F.P. of A. on the star globe is equivalent to the time given by the chronometer.

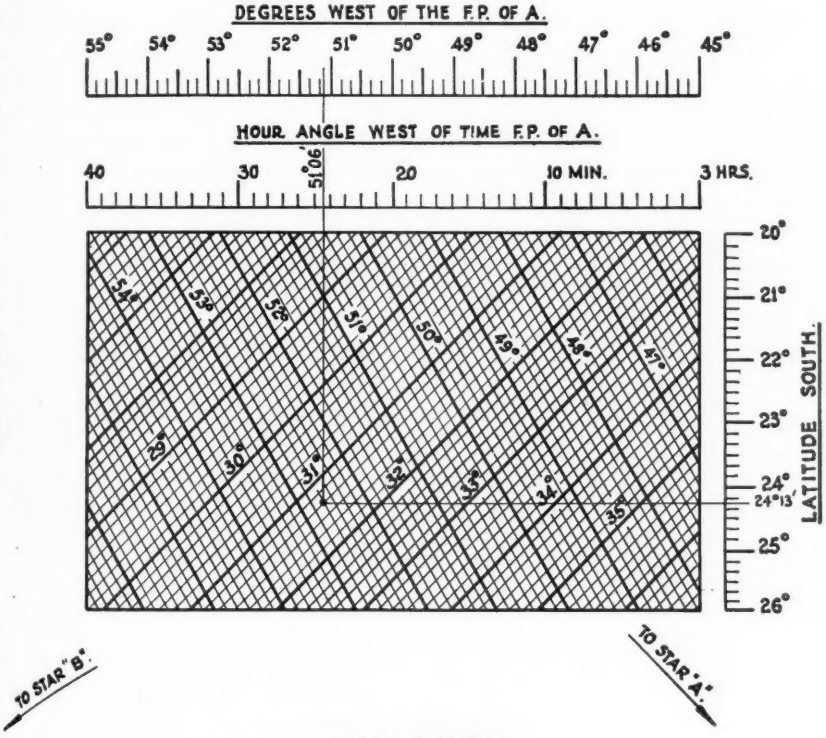
The relation of the stars to the earth at the time of making our observations is now shown exactly by the two globes, and a pin stuck through our position which we found upon the star globe into the earth globe beneath it, gives our position upon the earth.

In other words in order to find our longitude upon the earth we add the time (or the angle equivalent to it) to the hour angle of our position upon the star globe.

MAPS AND CHARTS.

In the ordinary way when travelling, instead of an earth globe we use a map or chart, a flat sheet of paper. Upon the map are the grid lines showing latitude and longitude, such as were drawn upon the globe.

In a similar way we can make a flat transparent map or chart of the transparent star globe showing the geo-position of the north and south poles, the geo-positions of the stars, the grid of the meridians or hour angles, the parallels of declination and the " position " circles about the geo-positions of each star.



STAR CHART.

FIG. 10.

The two maps or charts should be drawn to the same scale, one representing the features of the earth, the other representing the geo-positions of the stars, etc. By means of our position circles and by taking the altitude of two stars as before, we can find upon the transparent star map or chart the point where the position circles cut one another. This is our position, often termed our " cut," on the star globe. If we move the transparent star chart over the map beneath it so that the meridian of the First Point of Aries is the right number of hours or degrees ahead or behind the Greenwich meridian on the map, our true position on the earth is exactly beneath the position of our "cut " found on the transparent star chart.

In other words, by sliding the star chart over the earth chart we add two angles: (a) the time at which our observations were taken, and (b) the hour

angle of our " cut "; the total is the angle of our " cut " west of Greenwich. This is our longitude.

The declination of the " cut " on the star chart we already know. This is our latitude. We have thus found our position on the earth's surface and this is the object of navigation.

Star Charts.

Instead of having a transparent chart of the stars, the grid and geo-positions, etc., may be printed on ordinary paper. The grid showing latitude (or declination) and longitude (or time or hour angle) can also be printed upon it (Fig. 10).

Perhaps Fig. 10 needs some explanation. The larger the scale of the map we use the more exactly can we find our place in a country. The larger the scale of the star chart the more exactly shall we be able to judge the position of our " cut " in relation to the stars. In the star charts published for navigation the very large scale to which they are drawn results in a very large chart.

For convenience, the star charts are cut up, just as maps are, into sheets of handleable size, as in Fig. 10. Here the scale is so large that the position circles look like straight lines.

In this chart (Fig. 10) the group of parallel lines marked 30 degrees, 31 degrees, 32 degrees, etc., are parts of position circles drawn round the geo-position of Star A; Star A is located at a point far outside the part of chart which we are using and south and east of it. Similarly, the group of parallel lines marked 50 degrees, 51 degrees, 52 degrees, etc., are parts of position circles, drawn round the geo-position of Star B; Star B is located at a point far outside the chart and south and west of it.

Provided we have a suitable chart of this sort (use a star chart), the needed altitudes (use a sextant) and the time (use a chronometer) our position upon the earth can be found quite simply.

Thus, on this star chart (Fig. 10) the two altitudes are represented by their position lines: the " cut " or intersection of these lines is our " position." On the scale at the side of the chart we read the declination of our position on the star chart.

This is our latitude.

Again on the star chart: on the horizontal scale at the top of the chart we read the hour angle of the " cut." We can express this either as time in hours, etc., or preferably as an angle in degrees, etc.

From the chronometer we can get the time at which our observations were taken. We can express this either as time in hours, etc., or preferably as an angle in degrees, etc.

If the hour angle is the angle of our position west of the F.P. of A., and if the time is the angle of the F.P. of A. west of Greenwich, the two angles added together must be the total angle of our position west of Greenwich.

This is our longitude.

The Chronometer or Clock.

Let us give a little more thought to our chronometer or clock. In our method we make no use of " time " in the ordinary sense of the word. It is true that we read our chronometer or clock in hours, etc., but before the " time " is of any use to us we have to change it into an angle. We really use the clock as a measurer of angle—the angle swept out by the Greenwich meridian since last passing under the First Point of Aries. A lot of trouble is saved if the face of the clock is graduated in angle instead of in time. We then read our angle directly on the clock, add it straight to the hour angle of our " cut " and so get our longitude. Our type of chronometer then should be graduated in degrees, etc., instead of in hours. It is really not a time measurer but an angle measurer.

EXAMPLE (with explanation).

With the sextant, we take altitude observations of two stars and find altitude of Star B=52 degrees 40 min., altitude of Star C=31 degrees 20 min.

Using the appropriate star chart (Fig. 10) we find the point of the "cut" of our position lines to be: On the vertical scale 24 degrees 13 m2in. (this is the declination of our "cut" and is also our latitude); on the horizontal scale 51 degrees 06 min. (this is the hour angle of our "cut," or position of the "cut" west of the meridian of F.P. of A.).

The time at which we took our observations is given by chronometer say, 2 o'clock or 30 degrees. This tells us that at the time of taking our observations Greenwich meridian had passed the meridian of F.P. of A two hours ago, or by 30 degrees. Then our "cut" or position is 51 degrees 06 min. west of F.P. of A., and F.P. of A. is 30 degrees 00 min. west of Greenwich. Therefore our position is 81 degrees 06 min. west of Greenwich or 81 degrees 06 min. west longitude.

Our position is now found, viz.:—24 degrees 13 min. south latitude; 81 degrees 06 min. west longitude.

EXAMPLE (without explanation).

In the ordinary way all the above explanation would be left out and the actual working would run:—

Alt. B=52 degrees 40 minutes.	H.A.=51 degrees 06 min.
C=31 degrees 20 minutes.	Time=30 degrees 00 min.
Cut: Dec.=Lat.=24 degrees 13 minutes.	Long.=81 degrees 06 min.

Position 24 degrees 13 min. south lat.
81 degrees 06 min. west long.

We have thus found both latitude and longitude.

We have done what we set out to do.

We have found our position.

REVIEWS.

The First Century of Flight in America.

Jeremiah Milbank, Jr. Princeton University Press. 1943. $2.75.

The background of aeronautics is gradually unfolding itself throughout the world as research workers are making deeper studies into the gradual growth of flight. It is impossible to imagine that man from his early beginnings did not envy the birds and wish to fly. Many curious and disastrous attempts were made and mythology and early history abound with such flights of imagination.

To America fell the everlasting fame of making the first flight in a power-driven controlled heavier-than-air machine. Much pioneer work had been carried out in the United States before that, as in many other countries, and Mr. Milbank has done good service in preparing a history of the first hundred years in his own country. He has done it so well that it is to be hoped he will use his undoubted flair for historical survey to write another volume bringing his history up to date.

Following the first flight in a hot-air balloon by the brothers Montgolfier, and the use of hydrogen by Professor Charles, Benjamin Franklin became the first American sponsor of the new art. He wrote to the physician of the Empress Maria Theresa, in Vienna:—

> "It appears, as you observe, to be a discovery of great importance and what may possibly give a new turn to human affairs. Convincing sovereigns of the folly of wars may, perhaps, be one effect of it, since it will be impracticable for the most potent of them to guard his dominions. Five thousand balloons, capable of raising two men each, could not cost more than five ships of the line; and where is the Prince who can afford so to cover his country with troops for its defence, as that ten thousand men descending from the clouds might not in many places do an infinite deal of mischief before a force can be brought together to repel them?"

This letter was written in January, 1784.

One year later Blanchard and Jefferies made the first aerial crossing of the English Channel from Dover to France. Dr. John Jefferies was born in Boston, U.S.A.

The first actual ascent in America was made on June 24th, 1784, by a boy of 13 named Edward Warren, in a captive balloon, but it was not until January, 1793, that the first free balloon flight was made by the famous J. B. Blanchard, in the presence of George Washington.

Despite the publicity given to Blanchard's visit the new European craze did not seize upon the imagination of the Americans, for many years, despite spasmodic ascents by various balloon experts.

"The year 1830 marked the real inauguration of American aeronautical history," remarks Mr. Milbank. It was in that year that Durant began his series of ascents from New York. With the coming of the Civil War the value of the balloon for military purposes was demonstrated by T. S. C. Lowe.

In the eighties began the history of attempts to construct heavier-than-air craft, and in 1880 Edison himself began a series of investigations into the possibility of the helicopter. In 1883 Montgomery claimed to have made his first glider

flight in secret. The outstanding figure of the period, however, was Octave Chanute, the author of "Progress in Flying Machines." Chanute in 1890 proposed the founding of an American Aeronautical Society. From that time interest in the possibilities of heavier-than-air flight became greater every year and many men helped to blaze the trail which led to the final triumph on December 17th, 1903.

Mr. Milbank is to be thoroughly complimented on this survey of the first hundred years of flight in America.

THE AIR NAVIGATOR'S STARS.

By L. R. Glegg. Air League of the British Empire. 1943. 1/-.

A useful little pamphlet, consisting mainly of reprinted articles from the "Air Training Corps Gazette," intended for Air Cadets and pre-entry R.A.F. candidates. Explanations of the Celestial Sphere, Sidereal Time, and the apparent rotation of the stars, though simple, are clearer than is usual in this type of publication, and are illustrated by a number of diagrams. Further chapters deal with Star Maps, star groups at different times of year, the main stars used in air navigation, and latitude as affecting the star planisphere.

WINGS OF DESTINY.

The Marquess of Londonderry. Macmillan and Co. 12s. 6d. net. 1943.

This is an important book for it gives the history of the development of the Royal Air Force from its demobilisation in 1918 to its magnificent revival in 1940.

It is a depressing and a heartening history at the same time by one who did a great deal to fashion the shape of things to fly. "At a rough estimate, its strength," says the author, "at the end (of the Great War) was 30,000 machines." At the end of the war, indeed, this country had the most powerful air force in the world. In a few years it was to be so whittled away that it was only due to the miracle of superlative design of the machines being provided and the soundness of the training that it was not driven out of the sky by the Luftwaffe.

In those days of demobilisation Lord Londonderry was serving as Finance Member of the Air Council, and afterwards for a short while Under-Secretary of State for Air. It was not until November, 1931, that he became Secretary of State for Air and for the next two years the Disarmament Conference was in the forefront of European affairs. During that time this country reduced its Air Estimates while other countries increased theirs. Between 1925 and 1933 the Air Force estimates had been decreased by 8 per cent., whilst France in the same period had increased hers by 112 per cent. and the United States by 108 per cent.

How near we were to disaster not even Lord Londonderry will admit, although he was right in not admitting that Germany would strike over night in 1936, and that it would take at least three years before danger was really serious. But during those years much had to be done, and he knew it. "But I am quite sure the two things we should concentrate on," he wrote in that year, "apart from our activities to promote peace by proper contacts, are to see that we have a really powerful Air Force and that our Navy is kept up to such requisite strength as is required for policing our trade routes. I cannot help feeling that it is only a question of time before the Air will have the whip-hand of the Navy."

Lord Londonderry had many friends in high quarters on the Continent and could see clearly the inevitable catastrophe, and oddly enough for those very

reasons he was suspect in many quarters. "Because," he writes, "I hav tried to bring England and Germany closer together and so avoid the catastroph of war, many people have asserted that I was in favour of dictatorship." It wa an untrue assertion, without question.

The bitterness of this book can be read between the lines, the politic jockeyings which so very nearly lost the British race.

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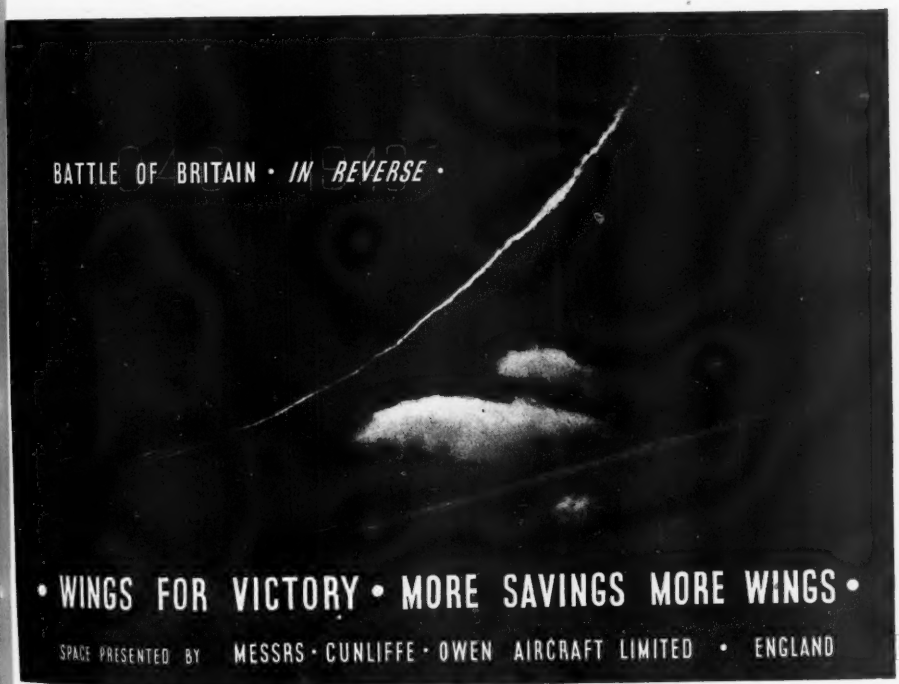
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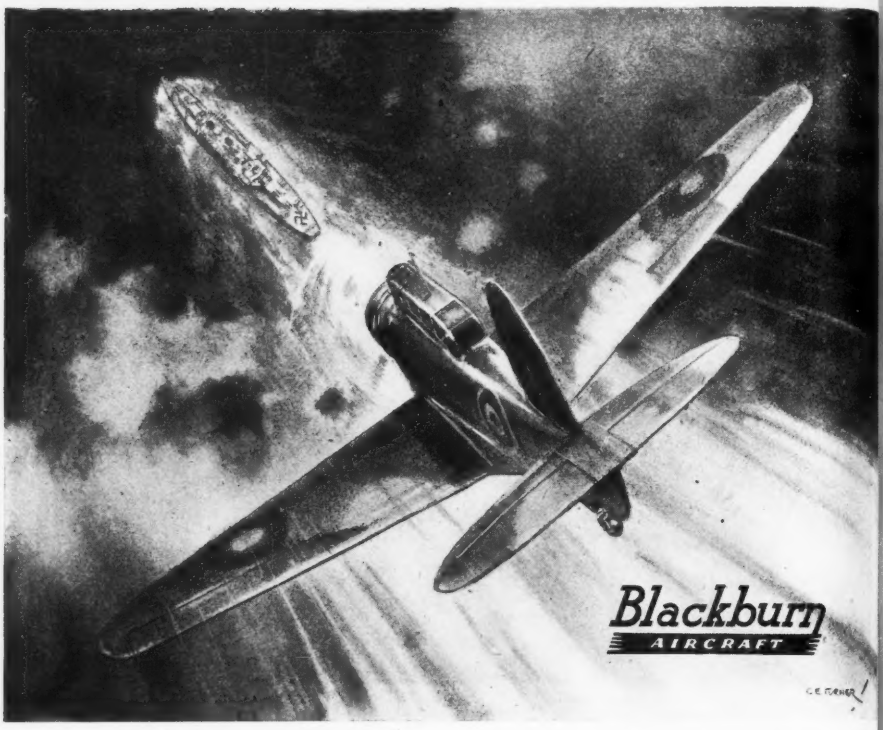

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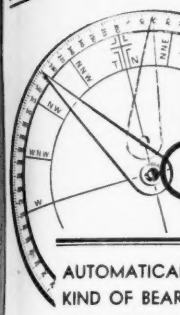

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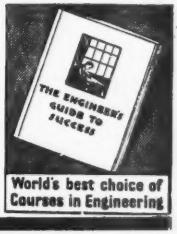

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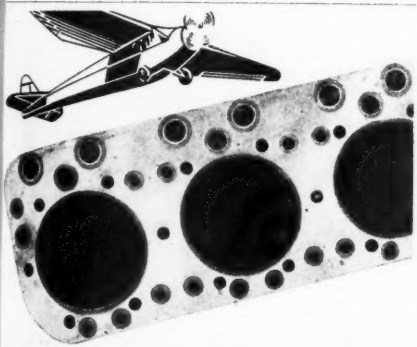

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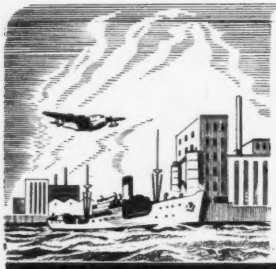

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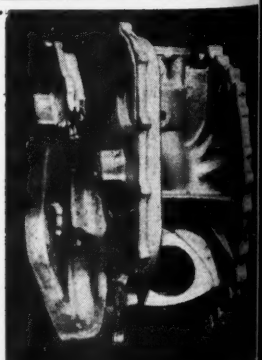

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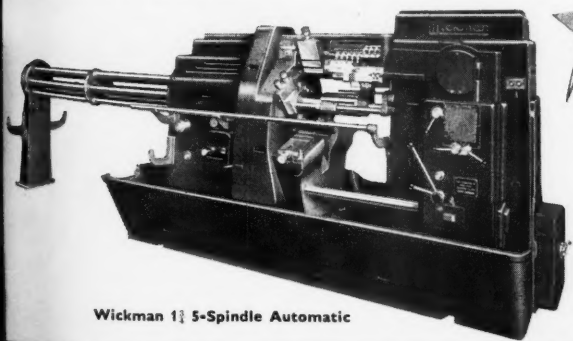

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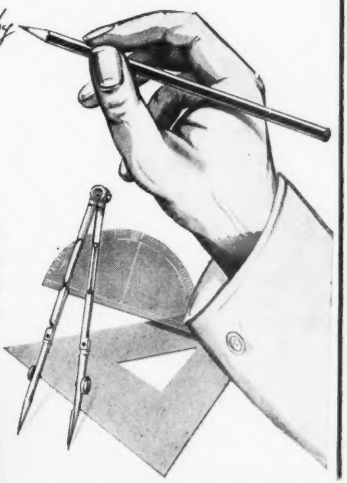

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